A METHOD OF FABRICATING A STEEL FORGING, AND A FORGING OBTAINED THEREBY

The invention relates to metallurgy, and more particularly to the field of steels for fabricating forgings that are to withstand high levels of stress.

Such forgings are often made of cast iron, particularly of perlitic structure sphroidal graphite (SG) iron, or out of ferrito-perlitic structure forged steel, which has the reputation of providing better resistance to fatigue than cast iron. Crank shafts for internal combustion (IC) engines constitute an example of such forgings.

Zones having high stress concentrations can be reinforced by various thermochemical, heat, or mechanical treatments, such as nitriding, induction quenching, deep rolling, or shot blasting.

Deep rolling applied to a crank shaft (this application not being exclusive) consists in putting two wheels into contact with the crank pin grooves. The wheels are oriented obliquely relative to the grooves and a normal force is applied thereto. The crank shaft is set into rotation and the normal force is applied progressively by the wheels during some number n_1 of revolutions, and is then maintained at a constant value for n_2 revolutions, and is then relaxed progressively during n_3 revolutions. This deep rolling generates residual compression stresses over a depth of 4 millimeters (mm) to 5 mm. It provides a significant improvement to the fatigue performance of SG cast iron of ferrito-perlitic structure. Nevertheless, because of the improved fatigue performance of the base metal, once crank shafts made of ferrito-perlitic structure forged steel have been deep rolled, their performance remains better than that of crank shafts made of SG cast iron. That is why it is preferred to use ferrito-perlitic structure steel in gasoline engines subjected to the highest levels of stress, and also in direct injection

diesel engines. It is also important to ensure that rupture does not occur outside the zones that have been reinforced, which justifies selecting a metal having high-performance characteristics.

Ferrito-perlitic structure forged steels that are often used for this purpose are of the types XC70, 45Mn5, 30MnSiV6, and 38MnSiV5, and after forging they are subjected simply to in-line cooling in still air. Their method of fabrication is thus relatively inexpensive, but their lifetime in the presence of high levels of stress is limited.

Proposals have been made for such parts to be made of bainite steel from a grade of the 35MnV7 type, with cooling after forging taking place under forced air. Strength performance is considerably improved over the preceding examples, but the method of fabrication is more expensive. In addition, it is not always possible to adapt the method to a manufacturing line initially designed to fabricate parts for cooling in still air.

The object of the invention is to propose an association between a grade of steel and a method of fabricating a forging, such as a crank shaft for an IC engine, presenting economical advantages compared with existing associations but without degrading metallurgical performance, and possibly even improving such performance. The part manufactured in this way must be capable of withstanding high levels of fatigue stress. The method of fabrication must in particular be suitable for being adapted to any forging line.

To this end, the invention provides a method of fabricating a steel part by forging, the method being characterized by the following steps:

· preparing and casting a steel having the following composition in percentages by weight: $0.06\% \leq C \leq 0.35\%$; $0.5\% \leq Mn \leq 2\%$; traces $\leq Si \leq 2\%$; traces $\leq Ni \leq 1.5\%$; traces $\leq Al \leq 0.1\%$; traces $\leq Cr \leq 1.5\%$; traces $\leq Mo \leq 0.30\%$; traces $\leq V \leq 0.5\%$; traces $\leq Cu \leq 1.5\%$; the

remainder being iron and impurities that result from preparation;

· forging a blank for the part at a temperature in the range 110°C to 1300°C:

· cooling the blank for the part in controlled manner in still or forced air;

· machining the part; and

· performing a mechanical reinforcing operation on the part at locations that are to be subjected to particularly high levels of stress.

The steel preferably contains five parts per million (ppm) to 50 ppm of B.

Preferably, the steel contains 0.005% to 0.04% of Ti.

If B is present, the Ti content is preferably equal to at least 3.5 times the N content of the steel.

Preferably, the steel contains 0.005% to 0.06% Nb.

Preferably, the steel contains 0.005% to 0.2% S.

In which case, preferably, the steel contains at least one of the following elements: Ca up to 0.007%; Te up to 0.03%; Se up to 0.05%; Bi up to 0.015%; and Pb up to 0.15%.

In a first embodiment of the invention, the C content of the steel lies in the range 0.06% to 0.20%.

The Mn content of the steel then preferably lies in the range 0.5% to 1.5%, and the Cr content preferably lies in the range 0.5% to 1.5%.

In which case, the Cu content of the steel may lie in the range 0.5% to 1.5%.

In another embodiment of the invention, the C content of the steel lies in the range 0.25% to 0.35%, the Si content lies in the range traces to 0.5%, the Mn content lies in the range 0.8% to 2%, the Cr content lies in the range 0.5% to 1.5%, the Mo content lies in the range 0.05% to 0.20%, the B content lies in the range 5 ppm to 50 ppm, and the Ti content lies in the range 0.005% to 0.04%.

In another embodiment of the invention, the C content of the steel lies in the range 0.20% to 0.35%, the Si content lies in the range 0.5% to 2%, the Mn content lies in the range 0.8% to 2%, the chromium content lies in the range 0.5% to 1.5%, the molybdenum content lies in the range 0.05% to 0.20%, the boron content lies in range traces to 50 ppm, and the Ti content lies in the range 0.005% to 0.04%.

In which case, annealing can be performed in the range 300°C to 500°C for a duration of 1 hour (h) to 3 h after machining or after controlled cooling in air and prior to machining.

The mechanical reinforcement operation may be deep rolling.

The invention also provides a steel forging characterized in that it is obtained by one of the above methods.

The forging may constitute a crank shaft for an IC engine.

In which case the mechanical reinforcement operation is preferably performed on the webs interconnecting the crank pins and the main journals of the crank shaft.

As will be understood, the invention consists in combining a grade of steel and a method of treatment after casting that includes a step of forging the casting, with cooling being performed in still air or in forced air, and with the zones of the casting that are subjected to the highest levels of stress being subjected to mechanical reinforcement. The selected steel composition guarantees that regardless of the way in which cooling is performed, forgings made from this steel and mechanically reinforced in the zones subject to the highest levels of stress have an ability to withstand fatigue that is sufficient to satisfy the requirements of users. Fabricating crank shafts for high performance IC engines is a particularly preferred application of the invention.

As a general rule, the criterion for determining whether or not a particular steel is suitable for the above-described uses is the fatigue endurance limit of the material initially in a non-cracked state, and taking account of residual stresses introduced in the surface by mechanical reinforcement operation.

The inventors have discovered that the above criterion, is, in fact, not pertinent. The residual stresses caused by deep rolling (or some other type of mechanical reinforcement) relax in the surface to a depth of several tenths of a millimeter as from first use, and the material cracks quickly over this depth. However, crack propagation is prevented because of the initial field of residual stresses imparted by the deep rolling. The decrease in stress concentration in the connection groove also performs this function. However no in-depth relaxation occurs.

The higher the pressure at which the deep rolling is performed, the greater the concentration of stress and the easier it is for cracking to occur. However, since the high pressure deep rolling has formed residual stresses over a greater depth, the cracking is blocked over greater distances and for greater moments, thereby limiting any risk of the part breaking. In general, it is nevertheless believed that, optimally, cracking ought not to occur, so as to avoid giving rise to resonances and to noises associated therewith when the crank shaft is in use, speaking only of this preferred application of the invention.

The chemical characteristics of the steel and the thermomechanical treatments applied after casting seek to obtain a bainite microstructure, and also to obtain mechanical characteristics after mechanical reinforcement treatment such as deep rolling that are optimized. The bainite microstructure must be obtainable following cooling in still air, but it must also be compatible with cooling in forced air. This enables parts made by the

method of the invention to be produced on any existing installation, regardless of whether it has provision for forced-air cooling after forging, or whether it makes use only of still air cooling. Thus, a forging installation initially designed for treating steel parts having a ferrito-perlitic microstructure can, without difficulty and without special adaptation, be used for treating parts of the invention having a bainite microstructure. The bainite microstructure steels previously used for such uses have required forced-air cooling and therefore could not always be treated on installations of common design.

In accordance with the invention, a steel is initially prepared having the composition that is described and explained in detail below, which steel is then cast in ingots or continuously depending on the format of the final part so as to obtain a half-finished product.

Thereafter, a forging operation is performed on the half-finished product. Forging is followed by controlled cooling in air in the heat of the forge, using still air or forced air.

Thereafter, the part is machined in conventional manner followed by a mechanical reinforcement operation at certain points that are going to be particularly heavily stressed when the part is in use. For a crank shaft, deep rolling is performed, for example, on the webs to which the crank pins are connected.

The analytic ranges required are as follows for the various chemical elements that must be present or that may optionally be present (all percentages are by weight).

The carbon content lies in the range 0.06% to 0.35%. This range serves to govern the type of microstructure that is obtained. With less than 0.06%, the resulting microstructure would not be advantageous for the intended objectives. Above 0.35%, in combination with the other

elements, the microstructure obtained after cooling in still air would not be close enough to bainite.

The manganese content lies in the range 0.5% to 2%. With more than 0.5% of this element, the material will be quenchable, and a broad bainite range can be obtained, regardless of the way in which cooling is performed. Nevertheless, a content greater than 2% would run the risk of leading to excessive segragation.

The silicon content lies in the range traces to 2%. This element is not strictly speaking essential, but it is advantageous insofar as it hardens the bainite by passing into solid solution. A content greater than 2% would nevertheless raise problems of machineability of the material. In addition, silicon impedes the formation of carbides and there would then be the risk of forming too much residual austenite, or indeed martensite in excessive quantity during cooling.

Nickel content lies in the range traces to 1.5%. This element is not essential but it encourages quenchability and stabilization of the austenite. If copper is present in relatively large quantity, then nickel serves to avoid problems associated with the presence of copper during forging. Above 1.5%, adding nickel is pointlessly expensive, given the intended metallurgical objectives.

The aluminum content lies in the range traces to 0.1%. This element is not essential but is a strong deoxidizer, and even when added in small quantity, it serves to limit the quantity of oxygen that dissolves in the liquid steel, thereby improving the inclusion purity of the part providing excessive reoxidization has been avoided during casting.

The content of chromium, a non-essential element, lies in the range traces to 1.5%. Like manganese, chromium contributes to improving quenchability. Adding chromium becomes pointlessly expensive above 1.5%.

The molybdenum content lies between traces and 0.3%. This non-essential element prevents large-grain ferrite forming and makes obtaining a bainite structure more reliable. Adding molybdenum becomes pointlessly expensive above 0.3%.

Vanadium content lies between traces and 0.5%. This non-essential element serves to harden the bainite by passing into solid solution. It becomes pointlessly expensive to add vanadium above 0.5%.

Copper content lies in the range traces to 1.5%. This non-essential element can improve machineability, and by precipitating, it can lead to secondary hardening of the material. As mentioned above, it is advisable for it to be associated with a significant content of nickel in order to minimize problems of shaping while hot. Above 1.5%, adding copper is pointlessly expensive.

The elements mentioned above are those whose metallurgical roles are or can be of greatest importance for the invention, however other elements mentioned below may optionally be present in order to improve certain properties of the steel.

The boron content may lie in the range 5 ppm to 50 ppm. It can improve quenchability, but it needs to be in solid solution in order to be effective. In other words, it is necessary to ensure that no or practically no boron is present in the form of boron nitrides or carbonitrides. For this purpose, it is advisable to associate adding boron with adding titanium, preferably at a concentration such that $3.5 \times N\% \leq Ti\%$. With this condition, all of the dissolved nitrogen can be captured, thereby avoiding the formation of boron nitrides or carbonitrides. For this reason, and given the lowest nitrogen contents that are usually encountered, the minimum titanium content is 0.005%. Nevertheless, it is advisable not to exceed a titanium content of 0.04%, since otherwise titanium nitrides of excessive size are obtained.

Titanium also has a function of limiting the extent to which austenetic grains grow at high temperature, and that is why it can be useful to add titanium independently of boron.

Niobium may also be added, at concentrations lying in the range 0.005% to 0.06%. It too can precipitate in the form of carbonitrides in austenite, and can thus serve to harden the material.

Finally, in conventional manner, the machineability of the material can be improved by adding sulfur (in the range 0.005% to 0.2%), which can be associated with the addition of calcium (up to 0.007%) and/or of tellurium (up to 0.03%) and/or of selenium (up to 0.05%), and/or of bismuth (up to 0.15%) and/or of lead (up to 0.15%).

Once the half-finished product having the above-specified composition has been obtained, the blank of the part is subjected to forging in conventional manner. It is heated to 1100°C to 1300C° and then subjected to deformation to provide a blank for the part, followed by trimming and finishing in the usual way.

Then, after forging, controlled cooling of the part is performed either in still air or in forced air. In general, the part is caused to cool at a rate that is less than or equal to 3°C/s in the range 600°C and 300°C.

The part is then machined in conventional manner under conditions that should be modulated depending on the hardness characteristics obtained.

Finally, the operation of mechanically reinforcing the part is performed in those locations that are subjected to particularly high levels of stress in operation. For the crank shafts of IC engines, this operation can consist in deep rolling the webs between the crank pins and the journals.

In order to obtain parts having characteristics that are optimized for various applications, the invention can be implemented in various ways.

In a first implementation of the invention, the carbon content is restricted to 0.6% to 0.2% so as to obtain a low-carbon bainite that is very suitable for work hardening. The manganese content should optimally lie in the range 0.5% to 1.5%, and the chromium content in the range 0.5% to 1.5%.

For these steels, the traction characteristics (elastic limit, strength) of the resulting product are not particularly high grade: typically traction strength Rm is about 800 megapascals (MPa) to 900 MPa, and the elastic limit Re is about 550 MPa to 650 MPa. However, these steels present good machineability, and this can be improved by adding copper up to 0.5% to 1.5%.

In other implementations of the invention, the carbon content is set to a higher value than in the first implementation, lying in the range 0.20% to 0.35% so as to obtain microstructure in the final product that is constituted by medium-carbon bainite. This structure provides the product with high grade mechanical characteristics immediately after controlled cooling in air.

If the carbon content lies in the range 0.25% to 0.35% and the silicon content is less than or equal to 0.5%, then a structure is obtained that is composed of upper bainite. With a manganese content of 0.8% to 2%, a chromium content of 0.5% to 1%, a molybdenum content of 0.05% to 0.2%, and boron and titanium contents complying with the recommendations given above, a part is obtained that presents good suitability for work hardening, traction strength of about 900 MPa to 1000 MPa, an elastic limit lying in the range 600 MPa to 700 MPa, and machineability that remains satisfactory, particularly in the presence of copper which may have begun to precipitate during cooling following forging.

If the carbon content lies in the range 0.20% to 0.35%, the silicon content in the range 0.5% to 2%, the manganese content in the range 0.8% to 2%, the chromium

content in the range 0.5% to 1%, and the molybdenum content in the range 0.05% to 0.2%, then a structure is obtained that is composed of mixed bainite (granular + upper). This structure gives the part good endurance and good ability for being mechanically reinforced by shot blasting, work hardening, deep rolling, pre-forming, etc. It is believed that the presence of relatively soft residual austenite improves suitability for work hardening, and thus the establishment of pre-stress by the mechanical reinforcing operation. The indentations of the grooves in the connection webs are relatively small, thus decreasing stress concentration and increasing resistance to cracking. Typically, traction strength of about 950 MPa to 1250 MPa, together with an elastic limit of 600 MPa to 800 MPa, which values are adjusted by the silicon content. Machineability remains accessible and can be improved by the additions described above for this purpose. The addition of boron (up to 50 ppm) and/or of titanium (up to 0.04%) can also be advisable for the reasons given above.

In this implementation of the invention, it is also possible to implement a small amount of annealing at 300°C to 500°C for 1 h to 3 h. This transforms the residual austenite into ferrite and carbides, thereby obtaining a small increase in the elastic limit without reducing traction strength. This improves resistance to fatigue by about 10%. The annealing may be performed after machining or after cooling but before machining.

Two applications of the invention and a comparative example are described below.

As is conventional when testing materials for crank shafts, the mechanical tests described below were performed on test pieces of a shape suitable for reproducing the stresses to which the connections of a crank shaft crank pin are subjected when subjected to bending, and the test pieces are subjected to a thermal cycle identical to that which is imparted by forging a

crank shaft. They are subjected to deep rolling under conditions analogous to that of the deep rolling conventionally performed on the webs connecting the crank pins of a crank shaft.

As a reference, tests were performed on test pieces of 38MnSiV5 type steel having ferrito-perlitic structure and the following composition C = 0.38%; Mn = 1.4%; Si = 0.5%; S = 0.075%; Ni = 0.1%; Cr = 0.2%; Mo = 0.03%; Cu = 0.02%; V = 0.09%; N = 130 ppm. Those test pieces were cut from steel that had been subjected to rolling following by cooling in still air (0.5°C/s to 1°C/s) which gave it traction strength of 860 MPa and an elastic limit of 570 MPa.

The deep rolling was performed using wheels inclined at 35° relative to the vertical, on grooves having a radius of 1.35 mm, with an undercut of about 0.6 mm. The loads applied during deep rolling lay in the range 800 decanewtons (daN) to 1200 daN.

Under those conditions, crack starting occurred for moments of 2090 newton meters (N.m) to 1850 N.m, and rupture moments of 4050 N.m to 4620 N.m were also obtained (it should be observed that as the applied load increases, the moment needed for starting cracks decreases, while the rupture moment increases).

The same tests were performed on steel test pieces of bainite structure corresponding to the invention and having the following composition: C = 0.24%; Mn 1.50%; Si = 0.7%; S = 0.077%; Ni = 0.1%; Cr = 0.8%; Mo = 0.07%; Cu = 0.1%; V = 0.19%; B = 30 ppm Ti = 0.019%; N = 70 ppm. This steel thus had a composition corresponding to the above-described high-carbon content implementation, in its high-silicon version where a mixed bainite structure is obtained after forging and cooling in still air (0.5°C/s to 1°C/s). No subsequent annealing was performed. Under those conditions, traction strength of 1000 MPa and an elastic limit of 640 MPa were obtained,

which is significantly better than for the reference steel.

A test piece was subjected to deep rolling under the same conditions as for the reference test piece, still with applied loads of 800 daN to 1200 daN.

Under such conditions, there were obtained crack starting moments of 2650 N.m to 2400 N.m, and rupture moments of 5200 N.m to 5900 N.m. The invention achieved a very significant improvement of these two limits, of about 30%.

The inventors explain this result by the test piece made in accordance with the invention being more suitable for a small amount of stress relaxation at giving loading. This produces greater blocking of cracks that have already started. The crack starting limit is improved because the wheels indent the grooves to a lesser extent: stress concentration is lower and traction strength is higher.

Using X-ray diffraction testing, the inventors have also observed that ordinary ferrito-perlitic steels are subject to greater softening than are steels of the invention, which on the contrary, even have a tendency to become stronger while in use.

The main advantage of the invention is that for lower deep rolling loads, the same results are obtained in terms of mechanical properties as with conventional ferrito-perlitic grades. It is thus possible to economize on deep rolling wheels, thereby reducing the cost of the deep rolling operation. This serves to compensate for the extra cost due to the greater presence of alloying elements in the steel.

Tests have also been performed on steel test pieces of bainite structure corresponding to the invention, and having the following composition: C = 0.06%; Mn = 1.35%; Cr = 0.90%; Si = 0.39%; Ni = 0.25%; S = 0.003%; Cu = 0.22%; V = traces; N = 0.007%; Mo = 0.09%; and B = 0.003%. The composition of that steel corresponds to the

first implementation of the invention. Cooling was performed under forced air at a rate approaching 2°C/s to 3°C/s in the range 600°C to 300°C. Under such conditions, traction strength of 820 MPa and elastic limit of 550 Mpa were obtained, which is comparable to the reference steel. The test piece was deep rolled under the same conditions as for the reference test piece, still with applied loads of 800 daN to 1200 daN. Under those conditions, crack starting moments of 2300 N.m to 2500 N.m and rupture moments of 5600 N.m to 6120 N.m were obtained. In this case also, a very significant improvement of these two limits was obtained by using the invention, of the order of 20% and 35% respectively.

Finally, it should not be forgotten that the grades of steel used in the invention can be cooled equally well in still air as in forced air, which makes it possible for them to be treated on any existing forging installation.